Hot Dry Rock Geothermal Energy Development in the USA

by

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INTRODUCTION

One of the world's great untapped energy resources lies right beneath our feet in the form of hot dry rock (HDR), the common geologic condition at depth almost everywhere in the world. It has been estimated that there is enough heat in HDR at depths that can be reached with today's drilling technology to supply all the energy needs of the world for centuries to come (Edwards, et al. 1982) Natural sources of steam and hot water have long been used to provide heat and generate electricity at numerous locations (Duchane 1994). In fact, these hydrothermal energy resources, along with hydropower, are among the few nonfossil energy forms that have found widespread commercial application. Undoubtedly, the use of hydrothermal resources will continue to increase but hydrothermal areas are the exception rather than the rule and account for only a small and localized fraction of the world's store of geothermal energy. The real potential for growth in the use of geothermal energy lies in finding an efficient and economic way of extracting heat from the large, ubiquitous HDR resource.

HDR Technology. All recent HDR work is based on the concept outlined in a patent issued to the Los Alamos National Laboratory in 1974 (Potter, et al.). That patent describes the formation of a fully-engineered geothermal reservoir in hot, crystalline rock by the application of hydraulic fracturing techniques, and the subsequent circulation of water through that engineered reservoir to mine the thermal energy from the hot rock. For more than two decades, the US Department of Energy (DOE) has sponsored work at Los Alamos directed toward developing heat mining technology to the point where extraction of the energy from HDR is practical and economic.

The HDR process is relatively simple: A well is drilled into hot, crystalline rock. Water is then injected at pressures high enough to open the natural joints in the rock. The water flows into the dilating joints and an engineered geothermal reservoir is thereby created. The reservoir consists of a relatively small amount of water dispersed in a large volume of hot rock. The relative dimensions and orientation of the reservoir are determined by the local geologic and in-situ stress conditions, while its ultimate volume is a function of the injection pressures applied and the duration of the hydraulic fracturing operation. Seismic techniques are used to follow the growth of the reservoir and to assess its location and approximate dimensions (House 1987). Using the microseismic data as a guide, one or more additional wells are subsequently drilled into the engineered reservoir at some distance from the first well. In a properly engineered HDR reservoir, there are a number of fluid-flow pathways between the injection and production wellbores

To operate the heat mine, a high-pressure injection pump is used to circulate water through the engineered reservoir in a closed loop as shown in Figure 1.

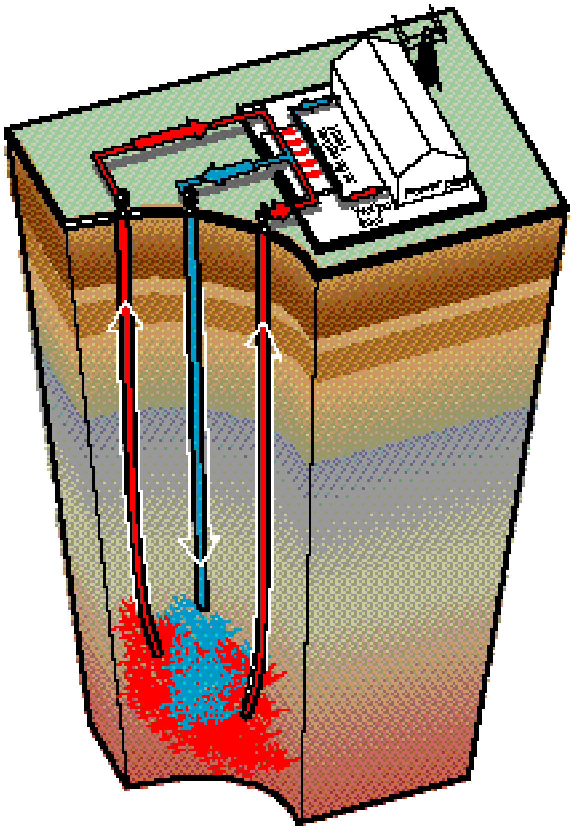

Figure 1. An HDR heat mining system. Water is circulated around a closed loop to extract thermal energy from an engineered geothermal reservoir and deliver it to a power plant on the surface. A high-pressure injection pump provides the sole motive force.

The injection pump provides the sole motive force for moving the water continuously around the loop to mine energy from the reservoir and deliver it to a power plant on the surface. The hydraulic pressure applied via the injection pump also serves to keep the joints within the reservoir propped open (Brown 1991). The operating parameters applied to the injection pump thus greatly affect both the flow rate through the reservoir and its instantaneous fluid capacity. By using a combination of injection and production control measures, an almost limitless variety of operating scenarios may be employed to mine the heat from an HDR reservoir

HDR RESERVOIR DEVELOPMENT AND INITIAL TESTING AT FENTON HILL

Numerous hot springs and other geothermal features provide evidence of the high heat flow in the Jemez Mountains of northern New Mexico, an area dominated by the Valles Caldera, a dormant volcano. Field work to demonstrate the HDR concept began in 1971 with reconnaissance heat flow measurements in various parts of the Jemez Mountains, followed in 1973 by a series of hydraulic fracturing experiments in a 730-m-deep exploratory borehole on the western flank of the caldera. In 1974, a permanent test facility was established at Fenton Hill, about 60 km by road west of Los Alamos. The Fenton Hill site lies about 2.8 km west of, and outside, the ring fault structure of the Valles Caldera that defines the boundary of recent (60 000 years ago) resurgent volcanic activity. The basement rock at a depth of 2400 to 4200 m beneath the surface of Fenton Hill is composed of a highly jointed Precambrian plutonic and metamorphic complex. Other than an elevated geothermal gradient (about 64°C/km), the only volcanic association of the reservoir rock is in the contained pore fluids which are high in dissolved carbon dioxide, and contain trace amounts of hydrogen sulfide.

While Fenton Hill was selected primarily on the basis of favorable heat flow and the lack of structural complexity in the anticipated reservoir rock, its location on a paved road made it easy to bring in heavy equipment. In addition, although the western flank of the caldera is heavily forested, a fire had destroyed much of the vegetation at the Fenton Hill site. Thus, the environmental impact of the project in this highly scenic area was small. Finally, the Fenton Hill site, as a part of the Santa Fe National Forest, was under the jurisdiction of the US Forest Service. It was therefore a simple matter to arrange an inter-governmental agreement to transfer management (but not ownership) of the land to the DOE. Los Alamos could then operate the site under its role as a contractor to the DOE. For all of these reasons, Fenton Hill appeared to be a good permanent site for carrying out HDR research and development.

The Phase I HDR Reservoir. Development of the world's first HDR system was initiated at Fenton Hill in 1974. The first borehole was drilled in granitic rock to a depth of 2900 m where the temperature was 197°C . After a series of hydraulic fracturing experiments, a second wellbore was drilled toward the largest of the near-vertical, stimulated natural joints. A good connection was not immediately achieved, and sidetracking was necessary to establish contact with the initial well via a combination of induced and natural fracture pathways.

The Phase I system was evaluated in a series of flow experiments from 1978 to 1980 (Dash et al. 1980). In the first flow test, water was circulated through the reservoir for 75 days in early 1978. The significant thermal drawdown (from 175°C to 85°C) indicated that only a small heat transfer area existed. A second 28-day test in late 1978 assessed the effects of imposing a high backpressure on the production wellbore. This strategy was found to reduce flow impedance but not to increase the surface area of heat extraction. The reservoir was then enlarged by further hydraulic fracturing and two more flow experiments were conducted: First, a flow test lasting 23 days was carried out to quantify the operating performance of the enlarged reservoir. This was followed by a 286-day heat extraction flow test during which the reservoir temperature declined from an initial value of 156°C to a final level of 149°C .

At the end of this series of flow tests, a short stress-unlocking experiment was performed. It entailed applying an elevated pressure to the reservoir in order to facilitate relative movement of joint surfaces and the resulting redistribution of fluid flow and/or the opening of new fluid pathways in the cooled reservoir rock. There were abundant indications of seismic activity within the reservoir during the pressurization experiment, and subsequent flow measurements suggested that the reservoir impedance had indeed been reduced. However, the system was not operated long enough following the stress-unlocking experiment to demonstrate that the improved flow conditions could be maintained for an extended length of time.

The pioneering work with the Phase I HDR reservoir proved that heat could be extracted from HDR using the techniques conceived and developed at Los Alamos. In addition, it indicated that issues such as induced seismicity, water consumption, and fluid geochemistry (including its effect on the system components), would not present insurmountable problems in operating an HDR heat mine. This initial field work highlighted the dynamic nature of HDR reservoirs, even under steady-state operating conditions, and laid the groundwork for the development of strategies to increase the productivity of future HDR reservoirs

The Current HDR Reservoir. Taken together, the hydraulic fracturing operations employed to create and enlarge the Phase I HDR reservoir involved the injection of about 2000 m^3 of water. The rapid cooldown of that reservoir indicated the need to create a much larger and hotter HDR reservoir in order to produce energy at the high rates and temperatures required for commercial power production. For this reason, plans were developed for a Phase II HDR reservoir which would be larger, deeper, and hotter. These plans were based on generalizations about the formation of HDR reservoirs, some of which later proved to be incorrect.

The results of work with the Phase I reservoir led to the assumption that hydraulic fracturing typically resulted in the formation of thin, vertical fractures in the intact rock, and that the size and heat production capability of an HDR system could be manipulated by employing a number of fracturing operations in isolated sections of a single wellbore to induce multiple, independent vertical fractures of this type. Until these preconceived notions were cast aside, extreme difficulties were encountered in the creation of a viable Phase II HDR system

In 1980, under the auspices of the International Energy Agency, Japan and Germany joined the US HDR project. Both countries contributed funding and personnel to the project for the next five years, and the Japanese continued to be a part of the program for one additional year. Development of the Phase II system by this international group took place at the Fenton Hill Site within a few hundred ft of the Phase I wellbores. Work proceeded under the assumption that hydraulic fracturing would lead to vertical fractures as discussed above. Therefore, two wells were drilled before any fracturing was attempted. The deeper well was drilled to a vertical depth of 4390 m with the bottom 1000 m directionally drilled at an angle of 35° to the vertical. The temperature of the rock at the final depth was 327°C. The second well was drilled in a similar manner to the first, but with the inclined section located 380 m vertically above the lower wellbore. The intent was to position the wellbores so that a number of individual vertical fractures, far enough apart to be thermally isolated from one another, could be created to connect the two wellbores.

A number of fracturing operations were conducted between 1982 and 1984. During the largest of these in December 1983, over 21 000 m^3 of water (more than 10 times what was injected during all the experimental work with the Phase I system) was injected into an isolated zone of the lower wellbore located at a depth of 3520 - 3540 m. The pumping was carried out over a period of 2-1/2 days at injection pressures averaging 48 MPa. Neither this operation, nor any of the other hydraulic fracturing experiments resulted in a flow connection between the two wellbores. Furthermore, microseismic data indicated that the reservoir was developing approximately along the trajectory of the inclined portion of the lower wellbore in such a way that a connection between the two wellbores would never be established.

It was then decided to sidetrack and redrill the upper wellbore with the goal of penetrating the reservoir volume indicated by the microseismic data. Sidetracking was initiated at a depth of 2830 m. Drilling continued to a final depth of 4018 m where a bottomhole rock temperature of 265°C was measured. The sidetracked well penetrated the reservoir and intersected a number of joints that had been opened during the large (21 000 m^3 hydraulic fracturing operation described above. A small amount of additional stimulation produced good flow connections between the two wellbores. A cross-section view of the underground portion of the Phase II HDR system is shown in Figure 2.

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Figure 2. ThePhase II HDR reservoir at Fenton Hill, NM. The reservoir is ellipsoidal with its major axis tilted about 30° from the vertical. It is centered at a depth of about 3660 m, and has an effective volume of appproximately 16 million m^3.

The experience of five years of drilling, fracturing, and redrilling led to a complete change of thinking in regard to the nature of the fractures produced in HDR reservoirs. Extensive microseismic analyses and geologic evidence had indicated that the original concept of vertical flow passages created by actually forming new fractures in the basement rock was incorrect. Instead, all the evidence pointed to the opening of existing, but previously sealed, joints. As might be expected, the initial joint openings were found to occur in a direction approximately orthogonal to the least principle earth stress.

Simple geometric evidence indicates that the Phase II reservoir has a flow-connected volume of about 16 million m^3, and is ellipsoidal in shape, with axes ratios of approximately 3, 2, 1, respectively (Winchester 1992). The longest axis tends north-south, the shortest axis lies in an approximately east-west direction, and the intermediate axis is tilted approximately 30° from the vertical. The reservoir is penetrated by two wellbores, each of which terminates in an open-hole zone approximately 300 m in length. The distance between the two wellbores at the open-hole depth averages 110 m.

The Fenton Hill Surface Plant. Between 1987 and 1991, a surface plant, designed to meet power-industry standards and capable of extended operation, was constructed and mated to the large HDR reservoir. Figure 3 shows the principle components of the surface plant.

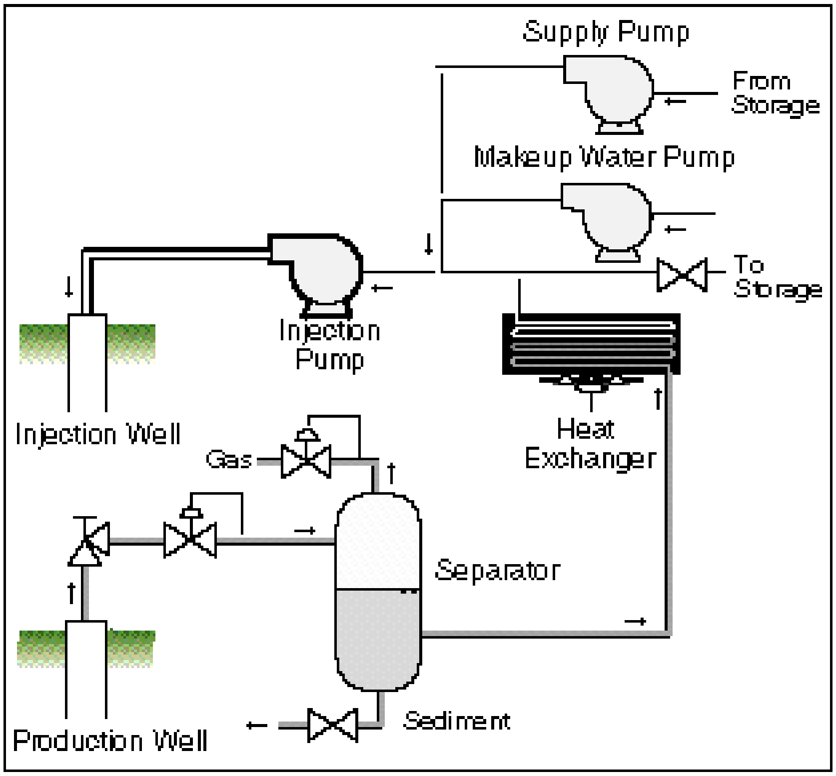

Figure 3. Schematic drawing of the surface plant at Fenton Hill. The injection pump circulates water from the injection well, through the HDR reservoir, out of the production well and around the surface loop. The plant is highly automated an instrumented at numerous points (not shown).

The heart of the surface plant is the injection pump which supplies the motive force for moving the fluid through the circulation loop. Originally, two diesel-powered reciprocating injection pumps were installed in the surface plant. These were designed for use on an alternating schedule, with one pump in operation and the other in reserve at any point in time. The pumps could be adjusted for operation over a wide range of pressures and flow rates. Each was capable of injecting a maximum volume of about 11 l/s of water at pressures as high as 34.5 MPa. For reasons unrelated to HDR technology, both these pumps failed within a span of two days during a period of normal operations. Several months of intermittent operations passed before a rented centrifugal pump powered by electricity was installed in the system. While lacking operational flexibility, the electric pump was extremely simple and very reliable. This original centrifugal pump was returned to its owner in late May 1993. A pump of similar design but with a somewhat higher flow capacity was subsequently purchased and installed permanently at Fenton Hill when the decision was made to resume flow testing in 1995.

The injection pump, piping to the injection wellhead, both wellheads, the wellbores and all flow paths through the reservoir constitute the high pressure portion of the circulation loop. This part of the system has been built for operation at applied surface pressures of up to 34.5 MPa. The remainder of the loop, the low pressure side, includes a particle/gas separator, an air-cooled heat exchanger, a makeup water pump, and connecting piping. This part of the system is capable of operation at up to 6.9 MPa. It feeds directly back to the injection pump. The surface plant is designed for automated operation and instrumented for measurement of fluid temperature, flow, and pressure at numerous points in the loop (Ponden 1992).

Initial Flow Testing of the Present Fenton Hill HDR Reservoir. After several preliminary experiments, a 30-day, closed-loop flow test of the Phase II HDR reservoir was carried out in mid-1986 (Dash 1989). This test was run at two injection pressures, 26.9 and 31 MPa. Pumping rates at these two pressures were typically 10.6 and 18.6 l/s respectively. While about 40 microearthquakes were detected during the lower pressure part of the test, several hundred microseismic events were observed when the pressure was raised to the higher level. These microearthquakes occurred almost exclusively on the side of the reservoir away from the production well. In other words, reservoir growth appeared to take place in that portion of the reservoir which was isolated from the pressure relief provided by the production wellbore. On the surface, the production side of the loop was maintained at a pressure of about 3.4 MPa to prevent boiling of the superheated water or escape of the gases (principally carbon dioxide) dissolved in the circulating fluid.

This initial test was of short duration, and was run with improvised surface equipment. In addition, the flow was interrupted a number of times during the 30-day test period. While this test did not generate data that could be used to demonstrate the routine operation of an HDR reservoir because steady-state operating conditions were never definitively established, it did show that the two wellbores penetrating the reservoir were well-connected and that energy could be produced at significant rates.

STEADY-STATE PRODUCTION TESTING AT FENTON HILL

Goals and Design. A series of flow tests of the Phase II HDR reservoir was conducted between 1992 and 1995. During 1992-1993 a long-term flow test (LTFT) program was carried out to demonstrate that the Phase II HDR reservoir at Fenton Hill and, by implication, HDR reservoirs in general could be operated on a continuous basis to produce useful amounts of energy over extended periods of time. The LTFT was designed to obtain information about the expected thermal lifetime of the Fenton Hill HDR reservoir, water consumption, operating and maintenance costs, and the geophysical, geochemical and environmental effects of long-term operation of an HDR system.

As a result of intensive discussions with the HDR Program Industrial Advisory Group, the LTFT was conducted under conditions simulating as closely as possible the operation of a commercial HDR power plant. The pressure under which water was pumped into the injection wellbore was adjusted to the highest level that could be maintained without leading to expansion of the reservoir volume, as indicated by the onset of microseismic activity and an increased rate of water consumption. Experience had shown that for the Fenton Hill reservoir this pressure was just under 27.6 MPa At the end of the LTFT, special flow testing was continued for several additional weeks to investigate techniques to improve the productivity of the HDR reservoir (Brown 1993). The reservoir was then placed on standby status for two years.

In May 1995, circulation through the reservoir was resumed in the form of reservoir verification testing. The purpose of the 1995 flow testing program was to ascertain the condition of the HDR reservoir after two years of dormancy, to demonstrate that the steady-state operating conditions of the LTFT test period could be re-established, and to further explore methods for maximizing the productivity of the system at Fenton Hill After the close of the steady-state phase of testing in 1995, a cyclic flow-test experiment was conducted to evaluate the potential of HDR reservoirs to produce baseline energy at baseload rates that could be rapidly increased to meet changing demand This form of energy production can be referred to as load-following.

Steady-State Test Operations. During the LTFT and all subsequent testing, water was generally injected in the reservoir at a surface pressure of 26.6 MPa. A backpressure of 9.65 MPa was typically maintained on the production wellhead in order to prop open, by means of this imposed pressure, the fluid-carrying joints in the relatively low-pressure region of the reservoir immediately adjacent to the production wellbore. The system pressure was reduced to about 4.8 Mpa at the outlet of the production wellhead, and this pressure was maintained until the water was returned to the injection pump for repressurization and reinjection into the reservoir. The plant was computer-controlled, with fluid circulation maintained 24 hours a day under these constant operating conditions. For much of the test period, the facility was manned only during daylight hours. On a number of occasions, usually as a result of power failures caused by local weather conditions, the plant went into an automatic shutdown mode. The plant was then re-started either by an operator called in especially for that purpose or when the operating staff routinely arrived the next morning.

Important system parameters such as pressure, temperature, and flow rate were monitored continuously. Measurements of the geochemistry of the circulating fluid were made several times a week. Finally, diagnostic procedures such as production-well temperature logging and tracer analyses were implemented every few weeks or at critical junctures in the flow-testing program

Continuous operation of the LTFT began on April 8, 1992, and proceeded with only minor interruptions for 112 days. Catastrophic failures of both reciprocal injection pumps within a two-day period forced suspension of testing on July 31. Although the pump failures were not related to HDR technology, the ensuing lapse in testing while suitable replacement pumping capacity was being evaluated, procured, and installed, was a serious setback to the LTFT effort. By mid-February 1993, a replacement pump was in place at Fenton Hill and a second continuous phase of flow testing was begun. The new pump was a leased centrifugal unit powered by electricity. Once the appropriate modifications to the electric power supply at the site had been implemented, it proved to be highly reliable. The second continuous test period ran for 55 days until mid-April 1993, when the available funding was exhausted. The two steady-state periods of the LTFT were subsequently designated LTFT Phase 1 and LTFT Phase 2, respectively.

As mentioned above, the HDR system at Fenton Hill was shut in for two years upon the termination of flow testing in May 1993. In May 1995, operations were resumed using a new pump of centrifugal design built especially for the project by REDA Pump Company of Bartlesville, OK. The operational control pressures in effect during the LTFT were emulated in the first 65 days of the reservoir verification testing program of 1995.

Steady-State Flow Test Results Counting periods of intermittent testing and special flow testing as well as the 3 steady-state test periods, Water was circulated through the large HDR reservoir for a total of about 11 months during the period extending from April 1992 thorough July 1995

Results from the three significant periods of steady-state circulation are summarized in Table 1.

Table 1.
STEADY-STATE FLOW TEST DATA

Test Period	Apr - July 1992	Feb. - Apr 1993	May - July 1995
Continuous Flow Period*, Days	112	56	65
Typical** Fluid Production Rate, l/s	5.68	5.86	6.57
Typical** Fluid Production Temp., °C	183	184	185
Water Loss Data			
Loss as % of Injected Volume	12	7	14
After a Continuous Flow Period of — Mo.	3.5	1.5	1.25
And a Continuous Pressurization Period of — Mo.	6	15	2

*Continuous Flow means production more than 95% of time period.
**Except at start up, production flow rates and temperatures were within 5% of indicated typical value.

The data of Table 1 show typical values for the test periods represented in each column, and provide important insights into the operation of HDR energy extraction systems. First and perhaps foremost, the production temperatures of the circulating fluid remained consistently in the same range during all the flow testing. The small temperature variations among the data shown in the table closely correlate with differences in flow rates, and can be attributed to varying rates of energy loss to the rock surrounding the production wellbore as the fluid traveled the 3-km distance up the production wellbore from the reservoir to the surface. Logging data collected on a number of occasions showed essentially no change in the temperature of the fluid at the point where it entered the cased portion of the production wellbore.

Water loss data also showed consistent trends. High reservoir pressures were maintained over the span of the LTFT, including the interim period between the two steady-state phases of the test. As a consequence, water losses continually declined as the pressurization of the micro cracks in the rock at the periphery of the reservoir proceeded. By increasing the level of fluid pressurization in these microcracks, the pressure gradient to the far-field was slowly decreased, gradually reducing the outflow of fluid from the boundaries of the reservoir. Near the close of the LTFT in the spring of 1993, as shown in Table 1, the reservoir water loss had decreased to 7% of the injected volume, from an earlier value of 12%.

The reservoir verification flow testing of 1995 was initiated after a period of two years during which the reservoir pressure had been allowed to decay to a relatively low level of 10 MPa, and had then been maintained at this level by intermittent injection. During that two-year period, water flowed back into the reservoir from the overpressured region in the surrounding rock. Thus, at the start of the 1995 flow test, the reservoir and surrounding rock conditions were similar to those at the start of the LTFT in 1992 If the reservoir verification testing had been continued for an extended period of time, the water losses would have undoubtedly declined to the levels observed during the LTFT

In all the cases illustrated, the injection pressure and the production-wellhead backpressure were the primary control points. The injection and production flow rates, which are direct functions of these applied pressures, were stable during the two phases of the LTFT in spite of the fact that these test periods were separated by a six-month period of low-flow, sporadic circulation.

The flow rates observed upon the resumption of testing in 1995 indicated that some residual effects of a sudden flow-increase event that occurred during post LTFT testing in 1993 (Brown,

1993) persisted even after two years of reservoir dormancy. The most obvious process expected to occur during a long period of reservoir shut-in is temperature recovery at the surfaces of open joints within the reservoir. It thus appears at this time that localized reservoir temperature profiles may have played an important role in the initiation of the sudden flow increase and in its subsequent mitigation. Additional, well-designed flow experiments are required, however, if the effects of pressure, localized temperature, and other factors that may have led to some of the surprising production patterns observed since the close of the LTFT are to be fully understood.

TESTING OF THE LOAD-FOLLOWING POTENTIAL OF AN HDR RESERVOIR

Introduction. A 6-day cyclic load-following experiment (LFE), conducted in July 1995, has verified that an HDR geothermal reservoir has the capability for a significant, and very rapid, increase in thermal power output upon demand. The objective of this experiment was to study the behavior of the Fenton Hill HDR reservoir in a high-production-backpressure (15.2 MPa) baseload operating condition when there was superimposed a demand for significantly increased power production for a 4-hour period each day In practice, this enhanced production -- an increase of about 65% -- was accomplished by a programmed decrease in the production well backpressure over 4 hours, from an initial value of 15.2 MPa down to about 3.4 MPa. This relatively rapid depressurization of the wellbore during the period of enhanced production resulted in the draining of a portion of the fluid stored in the pressure-dilated joints surrounding the production well. These joints were then gradually reinflated during the following 20-hour period of high-backpressure baseload operation In essence, the HDR reservoir was acting as a fluid capacitor, being discharged for 4 hours and then slowly recharged during the subsequent 20 hours of baseload operation.

In this mode of operation, there would be no increase required in the reservoir size or number of wells (the *in situ* capital investment) for a significant amount of peaking power production for a few hours each day. Therefore, one of the advantages of geothermal load following over other US utility options such as pumped storage or compressed air energy storage (CAES) is that the HDR power plant would be operated during off-peak hours in a baseload mode, with an augmented return on investment compared to these other peaking systems which would normally not be operated during off-peak periods. Of course, the surface power plant and the geofluid reinjection pumps would need to be sized for the peak rate of thermal energy production, adding somewhat to the overall HDR system capital costs when compared to a simple baseload power plant design

The geothermal reservoir at LANL’s Fenton Hill HDR test site was most recently flow tested under steady-state conditions for an 8-week period from May through July of 1995 (Brown, 1995). At the end of this period, following 18 days of steady-state operation at a backpressure of 15.2 MPa, the 6-day series of cyclic flow tests was performed. For a period of 4 hours each day, the production flow rate was dramatically increased by a programmed reduction in the surface backpressure at the production well. Collectively, this series of cyclic flow tests is referred to as the load-following experiment (LFE), with the objective of studying the behavior of an HDR reservoir under a simulated demand for enhanced power production for a period of 4 hours each day.

The cyclic testing in 1995 followed a previous, shorter, 3-day cyclic test of the Fenton Hill reservoir in May 1993, at the end of the LTFT (Brown, 1994). At that time, 3 daily flow surges were performed to gain an understanding of how an HDR reservoir behaves during cyclic production For that testing, the reservoir had been produced for 16 hours at a very low flow and a very high backpressure, and then for 8 hours at a very high flow and a low backpressure (Brown and DuTeau, 1995). During the 1993 cyclic testing, the pressure at the injection well had been maintained at about 27.3 MPa by injection at a controlled, but variable, rate. The most striking feature of the 1993 cyclic production testing was the degree of enhanced production flow that was obtained for a period of 8 hours each day -- an average of about 9.15 l/s compared to a previous steady-state level of 5.7 l/s near the end of the LTFT in April 1993, for very similar injection conditions Funding limitations prevented further experimental investigation of this enhanced flow phenomenon until the summer of 1995.

Fluid Storage in Pressurized Joints Near the Production Well. Based on the results of extensive transient and steady-state flow and pressure testing over the past 10 years, it is apparent that the HDR reservoir at Fenton Hill is comprised of a sparse, multiply interconnected set of open joints in a very large volume of hot crystalline rock. The ratio of fluid to rock volume is of the order of 10^{-4} Within the body of the HDR reservoir, fluid is stored primarily in dilated joints which are mostly jacked open by fluid pressures that are well above the least principal earth stress. Therefore, the major part of the reservoir fluid storage arises from the elastic compression of the rock blocks between pressurized joints.

The pressure gradient across the body of the reservoir, from the inlet to near the outlet, is reasonably gradual However, within the 10-m ± region surrounding the production wellbore, the pressure gradient steepens markedly as the pressure drops to the level of the imposed pressure in the wellbore (imposed by the backpressure regulating valve at the surface) As a result, the joints are progressively more tightly closed by the earth stresses as the flow converges toward the pressure sink represented by the production wellbore This near-wellbore pressure gradient for the production well can be inferred from the set of transient shut-in pressure recovery profiles shown in Figure 4 (DuTeau and Brown, 1993)

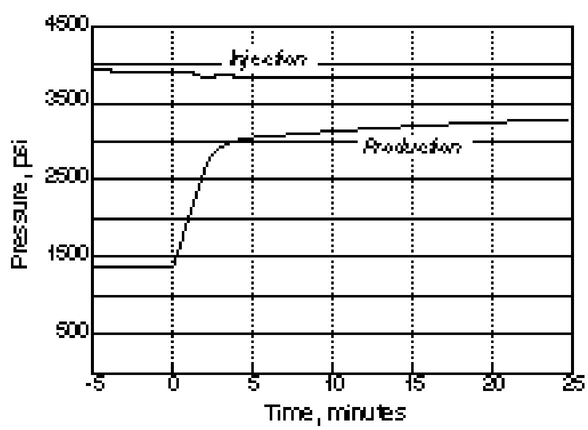

Figure 4 Transient Shut-in Pressure Profiles for the Injection and Production Wells.

This figure shows that when the production well was suddenly shut-in, the pressure measured at the surface (a direct measure of the downhole reservoir outlet pressure) rose from 9.65 to 20.7 MPa in less than 3 minutes, indicating that this high pressure level existed in the joint network very close to the production wellbore.

Conversely, when the production well backpressure is suddenly *decreased* from an elevated level of 15.2 MPa, this steep pressure gradient-region rapidly extends radially further into the body of the reservoir, effectively depressurizing and draining a significant zone of fractured rock surrounding the production wellbore. After 4 hours of continuous low-backpressure operation (following upon a longer period of high-backpressure operation), this zone of depressurized joints probably extends radially outward several tens of meters from the production wellbore.

July 1995 Load Following Experiment. Starting on July 3, 1995, the Fenton Hill HDR reservoir was again tested in a cyclic production mode, but now in a much more controlled fashion than the preliminary testing done in May 1993. This series of cyclic tests was begun from a well-established steady-state, high-backpressure operating condition that had been maintained for the previous 18 days (Brown, 1996). The operating data for the precursor steady-state reservoir flow test are given in Table 2.

Table I
1995 STEADY-STATE RESERVOIR PERFORMANCE AT A BACKPRESSURE OF 2200 PSI

Dates Measured:	June 27-29, 1995
Injection Conditions	
Flow Rate, gpm	124.2
Pressure, psi	3960
Production Conditions	
Flow Rate, gpm	99.0
Backpressure, psi	2200
Temperature, °C	183

Figure 5 shows expanded-scale profiles for the last two cycles of the LFE In flow control, the production well backpressure was continually and automatically adjusted by the control system to alternately maintain two essentially constant, but significantly different, production flow rates for these two 24-hour periods.

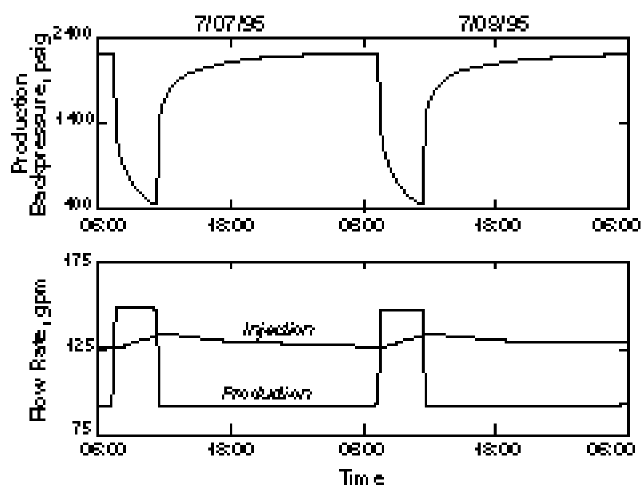

Figure 5 Last Two Cycles of the Load-Following Experiment.

Table 3 presents the reservoir performance data for the sixth cycle of the LFE. As shown in Table II, the actual mean flow rates for the sixth cycle were 9.25 l/s for 4 hours at a production temperature of 189°C, followed by 5.83 l/s for the subsequent 20 hours at a production temperature of 183°C. The peaking flow rate for the sixth cycle indicates a production flow enhancement of 59% over the baseload level of 5.83 l/s. When the higher temperature of the produced fluid is factored in, the corresponding increase in thermal power during the 4-hour enhanced production period was 65% over the baseload level of 3.72 MW The time required to increase the reservoir power output from the baseload to the peaking rate was about 2 minutes.

Table II
RESERVOIR PERFORMANCE RESULTS FOR THE SIXTH CYCLE OF THE LOAD-FOLLOWING EXPERIMENT

Averages	4-hr Peaking	20-hr Baseload	24-hr Overall
Injection Flow, gpm	129.3	129.6	129.6
Production Conditions			
Flow Rate, gpm	146.6	92.4	101.6
Temperature, °C	188.7	182.9	183.9
Thermal Power, MW	6.12	3.72	4.11

The average production flow rate of 6.42 l/s for the last 24-hour cycle was 3.9% greater that the steady-state level of 6.13 l/s existing on the morning of July 3, just prior to beginning the 6-day LFE. Similarly, the mean production temperature was 183.9°C, up slightly from the 182.7°C level existing on July 3. These average flow and temperature levels during cyclic operation show that there was also a meaningful overall enhancement in reservoir performance, due to the cyclic operation of the reservoir *per se*, when compared to preexisting steady-state levels at a constant backpressure of 15.2 l/s During the 1995 testing, this enhancement due to cyclic operation was almost enough to compensate for the previously measured steady-state flow decrease resulting from an increase in backpressure from 9.65 to 15.2 MPa, and the accompanying decrease in reservoir driving pressure (see Figure 6).

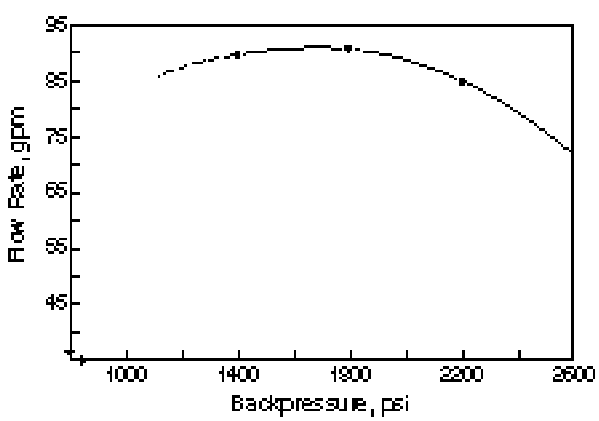

Figure 6 The Variation of Production Flow Rate with Backpressure for an Injection Pressure Level of 27.3 MPa, as Measured During the LTFT.

The production temperature profile for the sixth cycle of the LFE is shown in Figure 7 During the 4 hours of enhanced production, the production temperature increased from 181.6°C to 192.1°C, for a net temperature change of 10.5°C. This small change in temperature during the daily cycle of peaking power production should have a minimal effect on the integrity of the production casing and surface piping. In operations at Fenton Hill extending over the past 10 years, the production wellbore has been repeatedly cycled from full production temperature down to the geothermal gradient with apparently no adverse effects.

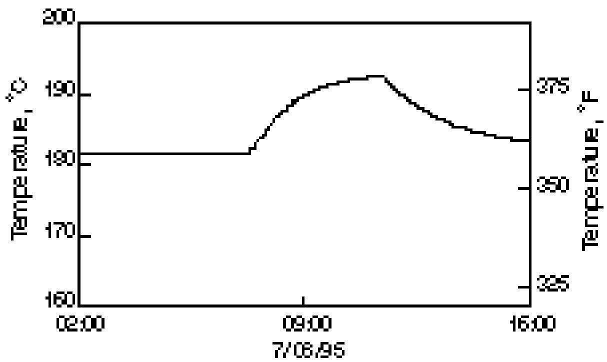

Figure 7 The Production Temperature Profile for the Sixth Cycle of the Load-Following Experiment.

Although we were able to achieve a power augmentation of 65% for a period of 4 hours each day during the LFE, there are several engineering approaches that could increase this peaking factor even more. For instance, for the LFE testing, we operated the reservoir at an injection pressure level somewhat below that required to open and extend the joint network at the periphery of the existing reservoir region. If the ambient pressure level of the HDR reservoir were to be increased to the maximum allowable pressure without reservoir growth, this would correspondingly increase the fluid storage in the pressure-dilated joints surrounding the production well, providing additional drainage volume for the transient periods of surging flow. In addition, since the properties of the fluid in an HDR reservoir are under our control, the composition of the fluid could be altered to allow a continued pressure drawdown below 3.4 MPa, down almost to the vapor pressure of the production fluid (1.24 MPa at 190°C). To implement this strategy at our Fenton Hill HDR site, it would be necessary to add an appropriate amount of ammonia to the circulating water to prevent the evolution of the dissolved CO_2 known to be present

Cyclic Testing Summary

A unique new method for operating an HDR reservoir to produce both baseload and peaking power has been experimentally demonstrated. In initial tests of this concept, an enhanced thermal power output of 65% for a period of 4 hours each day was obtained. This enhanced power output was obtained from a level of baseload operation that was within only a few percent of the previously determined optimum steady-state reservoir operating conditions. The principal objection to cycling the production from any geothermal reservoir has been the temperature cycling induced in the production wellbore. However, in this present method of surging the production flow, the temperature excursions were limited to only about 10.5°C.

Flow Testing Summary. Taken as a whole, the steady-state and cyclic flow tests conducted at Fenton Hill over the period of 1992-1995 demonstrated that HDR reservoirs can provide energy on a reliable basis, are extremely resilient, and have the potential for operational flexibility that goes well beyond the routine fashion in which geothermal reservoirs are normally exploited This series of tests provides a sound basis on which to develop a program for practical power production from HDR resources.

EMERGING DIRECTIONS OF HDR RESEARCH AND DEVELOPMENT IN THE USA

Commercialization of HDR technology has been a goal of the US HDR Program almost since its inception. With encouraging flow test results in hand, the DOE therefore issued a solicitation in December 1994 seeking an industrial partner to develop a facility to produce and market energy from an HDR resource. Bids were received from several organizations. In late June 1995, a technical review committee appointed by the DOE selected a winning bidder and recommended that the project go forward. Several months later, in October 1995, the DOE canceled the solicitation, stating that it would continue to pursue research and development on HDR but would defer commercialization efforts. Concurrently, a directive was issued to decommission the Fenton Hill site.

Announcement of a Restructured US HDR Program. The announcement that the US HDR Program would be restructured was first made by Karl Rabago, then DOE Deputy Assistant Secretary for Utility Technologies, in a speech at the opening of the Geothermal Resources Council meeting in Reno, Nevada on October 8, 1995. While that speech made the intent to restructure the HDR Program clear, it was vague on the goals and direction of the restructuring. A subsequent memo from the DOE Geothermal Division to the Department's Albuquerque Operations Office offered a little more insight into the future of the HDR program, stating:

> "Rather than pursue a commercialization goal, the Department will refocus the Geothermal Hot Dry Rock Program to work with industry and other interested parties to resolve the key technical issues. Los Alamos National Laboratory (LANL) is expected to play a continuing role in technology development."

The above statement makes two major assertions: 1) The HDR program will be refocused to work more closely with industry and other interested parties and, 2) Los Alamos National Laboratory will continue to play a role in HDR development. The "key technical issues" referred to in the memo have not yet been explicitly identified. One of the first tasks under the restructured HDR program entailed an attempt by the DOE Geothermal Division, industry, and other interested parties to delineate these key technical issues and formulate a plan to address them.

Initial Steps in Restructuring the HDR Program. In December 1995, the Geothermal Energy Association (GEA), at the direction of the DOE Geothermal Division, convened a geothermal industry panel to make recommendations on the future course of HDR research and development. The panel first engaged experts from the US geothermal industry, the national laboratories, other government agencies and foreign HDR programs in discussions of the status of HDR technology. It then met in executive session to develop a set of "industry" recommendations on the future course of HDR in the US These recommendations were immediately presented in preliminary form to Allan Hoffman, DOE Acting Deputy Assistant Secretary for the Office of Utility Technologies

In a report that so far has appeared only in "draft" form, but the essence of which was printed in the Geothermal Energy Association insert in a recent Geothermal Resources Council Bulletin (Wright 1996), that group affirmed the importance of HDR to the future of the geothermal industry, suggested that HDR technology should be integrated into the conventional geothermal industry, and proposed that the acronym "HDR" be replaced with a new term that would encompass all geothermal resources requiring artificial measures beyond current technology to achieve commercial heat extraction. They did not, however, offer any suggestions as to what the new term should be. The group also made the following specific recommendations:

- Unify management of all geothermal R&D programs and include HDR elements within the unified program.
- Convene a panel to formulate short- and long-term geothermal R&D goals, including the long-term commercialization of HDR.
- Establish a peer-review committee to evaluate the current status of the US HDR Program, publish its findings, and implement technology transfer to move HDR technology into the geothermal mainstream.
- Mothball the Fenton Hill site.
- Coordinate US geothermal R&D efforts with HDR programs in other countries.

Impending Restructuring Activities. The GEA panel offered some broad directions but few specifics in regard to the future course of HDR research and development. While the panel endorsed a much closer tie of HDR work to the goals of the hydrothermal industry, it gave no indications of exactly how to accomplish this. With this background, the DOE Geothermal Division now appears to be considering a dual approach to restructuring the HDR Program. This approach will move toward the vision of the United States as a "worldwide leader in the development, application, and export of sustainable, environmentally attractive, and economically competitive energy systems" as expressed in the DOE's strategic plan of April 1994. It will also address the more immediate concerns of the conventional geothermal industry. Two complementary groups are being considered to help set the course of future HDR work. One panel, under the auspices of the National Academy of Sciences, would review the status of the entire DOE geothermal program (including HDR) in depth, and would ideally provide a visionary outline of a path to eventual HDR implementation. The second group, more geothermal industry oriented, would address HDR in the context of its relationship to the conventional geothermal industry.

A National Academy of Sciences Review of Geothermal Research and Development in the USA. A review of geothermal energy development programs by a National Academy of Sciences (NAS) panel may the single most important factor in establishing a reinvigorated HDR Program. An NAS review would certainly be widely recognized as authoritative, independent, and unbiased. Hopefully, one result of an NAS review of geothermal programs would be a realistic assessment of the current state of HDR technology and a visionary plan to make HDR and the full range of geothermal resources, a key component of the clean energy supply the world will need in the 21st century

An NAS review could bring national stature to geothermal energy by focusing the attention of DOE upper management, other government agencies, wide segments of the energy and environmental communities, and the public at large, on HDR and geothermal energy in general. In this way, the review could help provide wider appreciation of the current contributions of geothermal energy to the nation's clean energy goals. Furthermore, recognition of HDR as a ubiquitous resource of national importance with a proven potential for deployment, would foster the increased public support for geothermal energy that will be essential if federal financial assistance to geothermal development is to be maintained in these times of shrinking national budgets.

A Geothermal Industry Review Board for HDR. The function of the geothermal industry review board will be to work closely with the DOE to define the specifics of the HDR Program. The board will assure that HDR is integrated into the mainstream of the geothermal research program, develop or endorse projects that apply HDR technology to the improvement of hydrothermal productivity, and advise the DOE on the direction of HDR work, especially in the near-term. Hopefully, the membership of the board will be drawn from the full spectrum of geothermal stakeholding organizations. Ideally, the geothermal industry HDR review board will be an ongoing entity that will first provide input to the NAS panel and then work with the DOE Geothermal Division to implement the NAS vision for HDR in a manner compatible with the aims of the geothermal industry. While the industry board may be charged with developing and prioritizing HDR projects, the DOE, acting as the agent of the US taxpayer, must make the final programmatic decisions in the face of budgetary limitations and broad departmental renewable energy goals.

Options for A Restructured HDR Program. The most important restructuring challenge is to formulate an HDR program that more closely allies the goals of HDR with the needs of the private geothermal industry, while at the same time holding to the central promise of HDR technology. That promise - transforming geothermal energy from its current perceived status as a localized resource with limited potential to that of a widely recognized world-class energy resource that will be one of the important contributors to providing the 21st century world with clean energy available virtually everywhere - must be met if the geothermal industry is to prosper and grow in the long run.

In order to reconcile the national HDR goals with the immediate interests of the conventional geothermal industry, a multi-faceted HDR effort will be required that: 1) applies HDR technology to the solution of near-term hydrothermal problems, 2) capitalizes on special opportunities to develop HDR technology in projects complimentary to hydrothermal technology, and 3) promotes international cooperation both to maximize the effectiveness of HDR research and development work underway in a number of countries around the world, and to assure US leadership in HDR development and marketing in countries that are just beginning to explore the potential of HDR as an indigenous energy resource. Each of these potential facets of a restructured HDR Program is discussed in more detail below

Industry-Coupled HDR Technology Applications. Cooperative Projects, which apply HDR technology and expertise to the solution of hydrothermal problems and increase the productivity of hydrothermal or quasi-hydrothermal (hot wet rock) reservoirs, have the potential to provide almost immediate benefits to the geothermal industry. During more than 20 years of work on HDR, unique capabilities in drilling, hydraulic fracturing, fracture location and characterization, reservoir engineering, logging tool design and application, reservoir development, and reservoir modeling have been put in place. In some instances, especially in areas such as drilling- and logging-tool innovations, significant technology transfer has occurred via the service companies that have at times been involved in the HDR project. However, in other areas such as reservoir engineering, fracture mapping and characterization, reservoir modeling, and reservoir development, there has as yet been little effective technology transfer to the hydrothermal industry

One aspect of a restructured HDR program might therefore be the formation of industry-coupled projects to apply HDR reservoir mapping and fracture location techniques to the identification and location of fluid-conductive fractures in hydrothermal fields. The information thereby generated could reduce the incidence of drilling "dry holes" and thereby markedly lessen field development costs. A second joint project might entail applying HDR expertise in injection and stimulation to make existing dry holes at hydrothermal sites productive and/or to develop engineered reinjection plans that would ensure that reinjected fluid (or supplementary injected fluid such as that to be delivered via the Geysers/Clearlake pipeline) is most effectively utilized to enhance energy production. Yet a third application of HDR technology might involve the application of HDR reservoir models to hydrothermal situations, particularly those concerned with reinjection or pressure maintenance and fluid production problems, in order to better understand how to limit declines in hydrothermal reservoir productivity.

The project areas described above are presented from an HDR perspective. Undoubtedly, industry engineers and scientists could modify them to most effectively meet the current hydrothermal research and development needs. Obviously, any of these projects are worth pursuing only if they have the solid support of one or more industrial organizations and can potentially contribute to improving the technical competence and competitive status of the US geothermal industry.

HDR Niche Development Projects. Cooperative projects which bring HDR technology to bear on hydrothermal problems will result in immediate useful applications of HDR technology, but this approach will not move geothermal energy toward the national stature needed to assure continued support from the federal government and the taxpaying public. In order to accomplish the latter goal, we must continue to pursue the development of HDR processes that can be implemented in those nonhydrothermal regions that underlay the vast majority of the US.

With the closure of Fenton Hill, a highly visible effort to advance heat mining technology in its widest sense - as a means of tapping the ubiquitous HDR resource - becomes more important than ever. This effort must include a continued search for a new site that can provide opportunities for field work in an HDR environment.

The knowledge base accumulated during field work at Fenton Hill can be applied to develop a new HDR site that may have practical as well as research and development applications. In view of the depressed price for electric power in the US, any such domestic HDR site must fit into either an especially attractive electricity niche (due to advantageous resource characteristics or local economic factors that lead to high electricity prices) or be located where there is an opportunity for a direct use application of the HDR energy. Direct use opportunities should be carefully evaluated and developed, as appropriate, in cooperation with private industry as well as state and local government entities that may have an interest in energy or economic development. Given the current bleak outlook for the electricity market the western part of the US where hydrothermal resources are found, niche applications of HDR may at present represent one of the few opportunities for additional domestic geothermal development. Finding a niche for HDR in today's highly competitive energy marketplace is a challenging task but, for all of the above reasons, it must be pursued if HDR and, indeed, the geothermal industry itself, is to have any chance of being a significant factor in the US energy picture of the future.

Increased International HDR Activities. HDR research and development has had an international flavor almost since its inception. The high point of international cooperation was reached during the period from 1980 to 1985 when Japan and Germany participated both financially and technically in the work to develop the large HDR reservoir at Fenton Hill. The international contacts made during those years have led to continued international cooperation in the form of periodic personnel exchanges and international meetings. For example, the 3rd International HDR Forum to be held in May 1996, at Santa Fe, NM, brought together about 100 HDR workers from Europe, Japan, Australia, and elsewhere to exchange information with their US colleagues and explore ways to work more closely together.

Efforts to increase international cooperation in geothermal energy via a new International Energy Agreement (IEA) have been underway for some time. The Japanese have taken the lead in the area of HDR and are proposing their New Energy and Industrial Development Organization (NEDO) be the operating agent for all HDR work conducted under the auspices of the IEA. Four project areas have been suggested for joint work. These include HDR economics, applications of hydrothermal technologies to HDR development, coordination of data acquisition and processing developments, and joint development of reservoir assessment technologies.

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